RESTRICTED CIRCULATION

This paper is not an official document; it is for information only and must not be quoted in any printed publication.

Agricultural Memorandum No. 892

A Proposed Cereal Yield Simulation Model

1. WHAT THE MODEL DOES

(1) Reads data for fixed calendar periods - maximum air temperature
minimum air temperature
duration of sun hours
daylength
radiation at the top of the atmosphere
green leaf area index
rainfall
number of days with 1 mm or more of rain
potential transpiration

(2) Computes water balance. Each calculation period is assigned its maximum available water for each of 3 soil layers, and the evaporation rate is assigned. Amounts of available water are calculated for the three layers together with a soil moisture deficit and excess rain. The ratio actual to potential evaporation is evaluated for the period.

(3) Computes the areas of sunlit and once-shaded leaves

(4) Computes average daily radiation total for the period

(5) Computes the average mid-day radiation intensity

(6) Computes mean daylight temperature (if needed)

(7) Assigns photosynthesis constants to allow for plant age

(8) Calculates mean daily gross photosynthesis

(9) Calculates gross photosynthesis for the period

(10) Multiplies gross photosynthesis by water stress factor

(11) Calculates synthesis and maintenance respiration

(12) Calculates total dry matter production

(13) Subtracts root dry weight

(14) Calculates grain yield using harvest index

Each of these sections is expanded below.

FH23

2. WATER BALANCE

The available water in the soil is divided into three portions. Each portion is available for extraction at a rate

$$F \times (PT)$$

where PT is the potential transpiration rate obtained either from MORECS or from the sunshine correction method in MAFF Technical Bulletin 16. F is a multiplying factor which takes into account the increased roughness of tall crops and the effect on stomatal resistance due to dry soil.

Figure 1 shows the three portions of available water from April to July for winter wheat, and figure 2 shows those for spring sown barley.

For winter wheat these amounts of available water were calculated from data given for a winter wheat crop grown at Sutton Bonington in 1975 (Gregory, McGowan, Biscoe and Hunter, 1978). For this crop the root distribution measured on 17 June was assumed to extract 150 mm of total available water. Half of this (75 mm) was assumed to be extractable at the potential transpiration rate, a third (50 mm) at a lower rate and the remaining (25 mm) at an even lower rate. These amounts of available water were distributed down the soil profile according to the measured root density. Table 1 shows the distribution of root density and water available at the potential rate on 17 June.

TABLE 1

Soil Layer (cm)	Root density on 17 June (arbitrary units)	Water in layer which can be extracted at the potential rate of transpiration (mm)
0-10	3.75	20.8 (=(3.75/13.52).75.0)
10-20	2.7	15.0
20-30	1.9	10.5
30-40	1.55	8.6
40-50	1.0	5.5
50-60	0.65	3.6
60-70	0.7	3.9
70-80	0.5	2.8
80-90	0.3	1.7
90-100	0.2	1.1
100-110	0.1	0.6
110-120	0.05	0.3
120-130	0.05	0.3
130-140	0.05	0.3
	13.52	75.0

From the measured root densities at other dates from February to June it was possible to calculate available water in 10 cm soil layers from d A/D, where d is the measured density, A is the available water in the 10 cm layer on 17 June, and D is the root density on June 17.

Figure 3 shows the total amounts of water available at the potential rate between February and June for winter wheat. All the points lie close to a straight line except in mid-May when it was thought by Gregory et al (1978) that tiller death had caused extensive root death as well. From the graph it is easy to extract average available water for the fixed calendar periods used in the model.

A similar method was used for spring barley by using data from Rothamsted in Wellbank (1975). The data are only for three dates in the growing season and for 15 cm layers (30 cm layers below 30 cm depth). Figure 4 shows the change of available water with time calculated from Wellbank's data. The model was intended to be used on spring barley data for Sutton Bonington which was sown 13 days earlier than Wellbank's crop. Because of this the curve was moved to the left, by 13 days early in the growing season, but progressively less later on, since the heading date was closer for the two crops. Figure 2 shows amounts of available water obtained for calendar periods from the adjusted curve.

During April the leaf area index for the Sutton Bonington spring barley was below 1.0 and bare soil can be safely assumed at least for the first two weeks. The maximum soil moisture deficit from bare soil was taken as 30 mm, and 9 mm was assumed to be extracted at the potential rate. The small increase in seedling growth was allowed for by increasing the maximum extraction at the potential rate to 11 mm in the second half of April. This bare soil part of the model does not take into account the frequency with which the soil surface becomes wet, which has been shown to be a major factor in evaporation from bare soil. Despite this drawback the model does restrict the maximum soil moisture deficit which can be reached, which is possibly the most important effect to incorporate.

F - factors

The F - factor was introduced at the start of the water balance section where it modifies the potential transpiration rate by allowing for the greater aerodynamic roughness of tall crops and the effect of increasing stomatal resistance. It can be written

$$F = F1 \cdot F2 \qquad (1)$$

F1 = factor which allows for increased aerodynamic roughness.

F2 = factor which allows for increasing stomatal resistance.

Table 2 shows the variation of F1 and F2 for spring barley and winter wheat. This table refers to 'average' phenology and would need to be modified for large variations in sowing date or seasonal temperatures.

TABLE 2. Variation of F1 and F2 with crop and time of year.

	WINTER WHEAT				SPRING BARLEY			
	F1	F2			F1	F2		
		Available Water				Available Water		
		First Half	Next $\frac{1}{3}$	Rest		First Half	Next $\frac{1}{3}$	Rest
1-15 April	1.0	1.0	0.2	0.1	1.0	1.0	0.2	0.1
16-30 April	1.0	1.0	0.6	0.36	1.0	1.0	0.2	0.1
1-15 May	1.0	1.0	0.6	0.36	1.0	1.0	0.6	0.36
16-31 May	1.0	1.0	0.6	0.36	1.0	1.0	0.6	0.36
1-15 June	1.0	1.0	0.6	0.36	1.0	1.0	0.6	0.36
16-30 June and after	1.18	1.0	0.6	0.36	1.18	1.0	0.6	0.36

F1

Thom and Oliver (1977) give an approximation to the Penman - Monteith formula for the latent heat flux from a surface as

$$E = \frac{\Delta Rn + [(\ln (Z/1.37))/(\ln (Z/Zo))]^2 \gamma Eap}{\Delta + \gamma (1 + r_s / r_a)} \qquad (2)$$

where the symbols have their usual meanings.

The effect of crop height on E enters mainly through Zo and r_a and

$$F1 = E1/E2 \qquad (3)$$

where E1 is the potential transpiration from the tall crop and E2 the potential transpiration from a short crop. If we use typical summer values of Δ = 1.23 mb/^{o}K, Rn = 3.15 mm water per day, also Z = 10 m, Zo = 20 mm (short crop about 20 cm tall) and Zo = 100 mm for the tall crop 100 cm tall, γ = 0.66, Eap = 2.48 mm water, and r_s = 50 sec/m as being a typical value for well watered crops. r_a is given by Thom and Oliver as

$$r_a = 4.72 [\ln (Z/Zo)]^2 / (1 + 0.54\ u) \qquad (4)$$

where u is the 10 m wind speed ($\sim$ 3 m/sec).

All these numbers put into equation (3) gives F1 = 1.18. In other words the potential transpiration from a crop 1 m tall with dry leaves is about 18%

more than the potential transpiration from a crop 20 cm tall. Values of the latter are available from the methods in MAFF Technical Bulletin 16 or MORECS. This approach is not rigorous and is only intended to obtain an approximate figure. Some experimental support comes from the Rothamsted Report for 1977, Part 1 which gives on P. 204 some transpiration figures measured by neutron moisture meter in a crop of irrigated barley. The measured evaporation in June and July was 1.24 that calculated by the "original Penman method", and this increase was attributed to the increased aerodynamic roughness of the barley compared with short grass. Thus there is some support that the 1.18 obtained above is at least not grossly misleading.

F2

This is the factor which allows for increasing stomatal resistance as the soil dries out. From equation (2) we can see that

$$F2 = \frac{\Delta + \gamma (1 + r_s/r_a) \quad \text{Dry Soil}}{\Delta + \gamma (1 + r_s/r_a) \quad \text{Wet Soil}} \qquad (5)$$

If we use the typical summer values of Δ, γ and wind speed as before it remains to determine r_s values as the soil dries out. Data is very limited on this point, but Russell (1980) is helpful. From this we can say (very approximately) that r_s = 50 sec/m as the water transpires at the potential rate for the first half of the available water, that $r_s \doteq$ 120 sec/m for the next one-third of available water, and that $r_s \doteq$ 210 sec/m as an average for the rest of the available water. With these values in equation (5) we get the values 0.6 and 0.36 as the F2 factors in table 2. This is an engineering approximation to a complex problem.

Interception

A treatment of the interception of rainfall is included in the model. Dew is not included. Spring barley and winter wheat are assumed in the model to intercept 1 mm of water each time it rains after the 15 June. Thus if there were 3 days between 15 and 30 June when the daily rainfall was 1 mm or more then the rainfall intercepted was taken to be 3 mm.

We have to have some idea of the evaporation rate of free surface water on the crop. Equation (2) can be used to compare the evaporation of surface water (r_s = 0) from a crop 1 m tall with transpiration from a short (20 cm tall) crop with r_s = 50 sec/m. If the typical summer values used above are inserted in the formulae then we find that the evaporation of free surface water from a crop 1 m tall is 2.45 that of the short crop potential transpiration. However, it is unlikely that this figure applies throughout the whole time that the intercepted water is evaporating, since the intercepted water is not uniformly distributed and r_s does not stay at the value zero all the time, but gradually rises to the dry leaf value (Monteith (1977)). As an engineering approximation it is assumed that intercepted water evaporates at 1.5 times the potential rate. Usually interception is a minor component of the water balance, but occasionally it can account for a moderate proportion of the rain that falls.

Suppose there are n days with 1 mm or more of rain during one of the fortnightly calculation periods. The amount of rain intercepted is n mm and this does not reach the soil. If R mm is the rainfall then (R-n) mm reaches the soil and enters into the soil moisture balance. The potential transpiration for the soil moisture balance is obtained as follows. If P mm is the short crop potential transpiration for a half month then P/15 is the potential transpiration for one day. Intercepted water evaporates at a rate 1.5 P/15 mm per day. Therefore, the time required to evaporate n mm of intercepted water is n/(1.5 P/15) days, and so the leaves of the crop are dry for (15-n/(1.5 P/15)) days. The potential transpiration rate from a dry crop is F1. (P/15) mm/day, so therefore the total potential transpiration for the 15 days to be used in the soil moisture calculation is F1. (P/15). (15-n/(1.5 P/15)) mm or F1 (P-n/1.5).

Ratio of Actual to Potential Transpiration

Actual evaporation from the crop is calculated as the rain which gets to the soil, (R-n) mm, plus the evaporation of intercepted water, n mm, plus the change in soil moisture content. The potential evaporation from the crop is evaluated as follows. From above n/1.5. (P/15) days is the time taken to evaporate n mm of intercepted water at a potential rate of 1.5 (P/15) mm/day. Therefore the potential evaporation when the crop has wet leaves is n mm, and the total potential evapotranspiration from the crop during the 15 day period is n + F1 (P-n/1.5). Thus the ratio of actual to potential evapotranspiration is

$$\frac{(R-n) + n + \text{change in soil moisture}}{n + F1.\ (P-n/1.5)}$$

which is the main result needed from doing a soil moisture balance, and it will be used later in the photosynthesis calculations.

3. AREAS OF SUNLIT AND ONCE-SHADED LEAVES

The method of calculating mean daily photosynthesis over 15 day periods is based on Monteith (1965). The sunlit leaf area Ao is

$$Ao = (1-S^{L})/(1-S)$$

where S is a light extinction factor and L is the leaf area index, Monteith suggests S = 0.7 as a general value for cereals, though values between 0.5 and 0.8 are quoted by various authors for barley.

The once - shaded leaf area is

$$A1 = (1-S^{L} - (1-S)\ LS^{L-1})/(1-S)$$

4. AVERAGE DAILY RADIATION TOTAL

Mean daily radiation for the 15 day periods was estimated from hours of bright sunshine using the regression formula (MAFF Technical Bulletin 16).

$$RAD = RA\ (0.16 + 0.62\ N/H) \qquad (6)$$

Where RAD is the mean daily radiation for a half month period. RA is the radiation at the top of the atmosphere; N and H are sun hours and daylength. Monthly values of RA are given in Technical Bulletin 16; these values were plotted on a graph on the 15th of each month, a smooth curve was drawn through the points and RA values for the 7th and 23rd of each month were read from the graph and used in the regression formula.

5. AVERAGE MID-DAY RADIATION INTENSITY

It is assumed that during a 15 day period the average diurnal variation of radiation can be expressed as $I^* \sin(\pi t/h)$, where I^* is the mean mid-day radiation intensity, t is time and h is daylength. The daily total of radiation RAD is given by

$$RAD = \int_0^h I^* \sin(\pi t/h)\, dt = 2 I^* h/\pi \qquad (7)$$

Since we know RAD from (6), equation (7) is used to obtain I^*.

6. MEAN DAYLIGHT TEMPERATURE

If photosynthesis is expected to depend upon temperature, it is necessary to calculate the average temperature during daylight hours. This assumes that photosynthesis is approximately linearly related to temperature so that an average can be used and that air temperature is a good approximation to the temperature at which the chemical reactions take place. The relationships given in Agricultural Memorandum 16 could be used for 15 day periods.

7. PHOTOSYNTHESIS CONSTANTS

Instantaneous rates of gross photosynthesis can be expressed by

$$P = (a + b/I)^{-1}$$

P is the gross photosynthesis (Kg of carbohydrate per m^2 of leaf area per second), b is a constant (209.3 J/Kg) and I is the radiation intensity (W/m^2). The term 'a' is the reciprocal of the maximum rate of gross photosynthesis when I is large.

Some data in Biscoe, Gallagher, Littleton, Monteith and Scott (1975) give values of gross photosynthesis for various leaves of barley plants. A considerable variation with leaf age is apparent which must therefore appear in the model. Before ear emergence leaves are produced in a steady succession at a rate of about one a week. The top two leaves are fully sunlit with the highest leaf on average being 3.5 days old and the leaf below it 10.5 days old. These ages give gross photosynthesis of 2.8 and 2.4 gm CO_2 m^{-2} leaf hr^{-1} respectively, with mean value 2.6. From Biscoe, Scott and Monteith (1975) we have

$$\text{Dry weight} = \frac{\text{Weight } CO_2 \text{ absorbed}}{1.46}$$

Hence the mean rate of maximum gross photosynthesis of the sunlit leaves up to ear emergence is 2.6/1.46 = 1.78 gm dry matter m^{-2} leaf hr^{-1}.

After ear emergence the graphs are used to estimate the photosynthesis rates of the flag leaf and the one below it (these are fully sunlit). For the 1-15 July we have the flag leaf at 2.1 and the next leaf 1.7, yielding an average of 1.9 gm CO_2 m^{-2} leaf hr^{-1} or 1.3 gm dry matter m^{-2} leaf hr^{-1}. For 16-31 July we have 1.3 and 1.0 for these two leaves which gives 1.2 gm CO_2 m^{-2} leaf hr^{-1} or 0.82 gm dry matter m^{-2} leaf hr^{-1}.

These maximum rates of gross photosynthesis are also applied to the 'once shaded' leaves even though they are older. Since most photosynthesis is produced by the sunlit leaves, errors caused by making this assumption are small.

8 & 9. THE CALCULATION OF MEAN DAILY GROSS PHOTOSYNTHESIS

Monteith shows that if the variation of radiation on a horizontal surface above the crop canopy is $I^* \sin(\pi t/h)$ as above, then the mean intensity that sunlit leaves experience is $(1-S)\, I^* \sin(\pi t/h)$.

Hence the instantaneous rate of photosynthesis of sunlit leaves is $(a + b/((1-S)\, I^* \sin(\pi t/h)))^{-1}$. The mean daily rate for all the sunlit leaves is

$$Ao.\quad 2\int_0^{h/2} (a + b/((1-S)\, I^* \sin(\pi t/h)))^{-1}\, dt \qquad (8)$$

For once - shaded leaves the radiation intensity is about one-tenth of unimpeded sunlight and the total photosynthesis of once-shaded leaves is

$$A1.\quad 2\int_0^{h/2} (a + b/((1-S)\, 0.1\, I^* \sin(\pi t/h)))^{-1}\, dt \qquad (9)$$

These integrals have been evaluated in terms of standard functions, and the sum of these two integrals is the mean daily rate of gross photosynthesis over the period for which AO, A1, I^* and h have been calculated.

10. THE EFFECT OF WATER STRESS ON GROSS PHOTOSYNTHESIS

The photosynthesis of a crop can also be expressed in terms of the carbon dioxide concentration and the resistances to diffusion between the air and the sites inside the leaf where photosynthesis takes place.

The relation is given by Monteith (1963) as

$$P = C/(r_a + r_s^* + r_i) \qquad (10)$$

C is the CO_2 concentration in the air.

r_a is the aerodynamic resistance of the crop.

$r_s^* = 1.7\, r_s$ is the crop stomatal resistance to CO_2 transfer.

r_i is the sum of the mesophyll and carboxylation resistances inside the leaf.

Equation (10) is only strictly valid when there is no production of CO_2 from the soil.

The value of r_i has been shown to be fairly constant over a wide range of leaf moisture conditions. Slatyer (1973) gives r_i = 300 sec/m (individual leaves) while Austin and Jones (1975) give 300-400 sec/m as typical. All these values are for wheat, and it is assumed that barley is very similar. If we assume a leaf area index of 5 then the canopy value of r_i is about 60 sec/m. For a crop 1 m tall we take the 'typical' mid-summer $r_a \doteq 17$ sec/m.

Therefore the ratio of photosynthesis for crop 1 with stomatal resistance r^*_{s1} and crop 2 with stomatal resistance r^*_{s2} is

$$P1/P2 = (r_a + r^*_{s2} + r_i)/(r_a + r^*_{s1} + r_i) \qquad (11)$$

If we take P2 as the photosynthesis for $r^*_{s2} = 1.7 \times 50 = 85$ sec/m, which is approximately the mean stomatal resistance to CO_2 when water is being transpired at the potential rate, then P1/P2 is the ratio of CO_2 assimilation as r^*_{s1} varies. The results are in table 3.

TABLE 3. Ratios of photosynthesis (equation 11) and transpiration (equation 5) at different values of r_s compared with r_s = 50 sec/m for a well watered crop.

r_s (sec/m)	50	75	100	125	150	200
F2 (Equation 5)	1.0	0.8	0.66	0.57	0.50	0.40
P1/P2 (Equation 11)	1.0	0.79	0.66	0.56	0.49	0.39

Here then is the link between the water balance calculations, and the effect of water stress on photosynthesis. The two ratios in table 3 are almost identical so the ratio of actual to potential transpiration can be used as a factor to be multiplied to expressions (8) and (9) to obtain actual gross photosynthesis.

11. RESPIRATION

The carbohydrate used in respiration was calculated according to a method given by Biscoe and Gallagher (1977) and Biscoe, Scott and Monteith (1975). These authors follow McCree (1970) and regard respiration as the sum of synthesis respiration, associated with the making of new cells, and maintenance respiration,

associated with the maintenance of the existing plant structure. Biscoe et al (1975) found for barley growing in the field that synthesis respiration is a constant fraction (0.34) of gross photosynthesis. Maintenance respiration is a function of the dry weight of the plant, and with the rate of respiration depending upon temperature according to a temperature coefficient (Q_{10}) relation of the form

$$R_2 = R_1 \, Q_{10}^{(T_2 - T_1)/10} \qquad (12)$$

where R_1 and R_2 are the respiration rates at temperatures T_1 and T_2 respectively (Biscoe and Gallagher (1977)). These authors set $Q_{10} = 2$ with the fraction of plant dry weight used in maintenance respiration equal to about 0.014 at a mean daily temperature (TM) of 20°C. A general expression for maintenance respiration is given by

$$(0.014 \times \text{dry weight})/(2^{(20 - TM)/10}) \quad \text{(per day)}$$

Since respiration takes place throughout the day and night, TM refers to mean daily temperature which is calculated as the mean of maximum and minimum air temperature measured in a standard meteorological screen. The daily range of temperature is fairly small ($\sim 10°C$) and the use of mean temperature in equation (12) does not introduce large errors.

12, 13 & 14. DRY MATTER PRODUCTION

The basic steps in the calculation of dry matter production are in figure 5. Gross photosynthesis represented by equations (8) and (9) is multiplied by the ratio of actual to potential transpiration and then synthesis and maintenance respiration are subtracted from this. This then gives total dry matter yield. At any time this will be partitioned between roots, stems, leaves and grain. When the crop is mature, measurements have shown that roots at this time represent about 10% of the total dry matter. If this is subtracted from the total dry matter, then this gives the total above ground dry matter at the end of the growing season.

Yield of grain can be obtained by using the idea of harvest index. Gallagher and Biscoe (1978) have collected several measurements of harvest index which show about 46% of the above ground dry matter appears as grain.

Application of the Model

1. Spring Barley. Crops of Proctor spring barley were grown at Sutton Bonington in 1972 (Biscoe, Scott and Monteith, 1975) and in 1975 (Gallagher, Biscoe, Scott, Dennis-Jones, 1977). For each of these crops frequent samples were made of whole crop yields (tops and roots) and leaf area index. A graph of the results is shown in figure 6 (for 1972) and in figures 7 and 8 (for 1975). The results for the 1972 crop also include some neutron probe moisture meter measurements of soil moisture deficit.

In 1972 (figure 6) the results show that the model matches the observed growth rate quite well in May, but that in June the model crop grows faster than was observed. The summer of 1972 was unusually cool, especially in June when the mean air temperature was 3°C below normal. This, together with ample rainfall, prolonged leaf life well into July. The crop was affected by mildew and although it was sprayed there is no evidence to suggest that control was complete. This may account for the lower observed growth rate in June. It is unlikely that soil moisture was limiting growth at this time with frequent rain and a deficit of about 50 mm.

Another point to mention is that at the end of July the model indicates a loss of total crop dry weight. This would appear to be an unusual feature of real crops and is probably because the model assumes that all dry matter respires. This may not be true during the final stage of growth when only the grains are growing and the leaves and stems are dying.

The observed grain yield in 1972 was 4.9 t/ha DM while the model gave 5.6 t/ha (allowing for 10% total crop DM in the roots and a harvest index of 46%).

In 1975 there were two sowing dates; one was early (February 20) see figure 7 and one late (May 4) see figure 8. It was expected that the root growth for the later sown crop would be less than for February or March sowings. Because of this the maximum available soil moisture was restricted to 100 mm, and the sequence of available water was from the first to the third, and finally the fourth 'column' in figure 2. The summer of 1975 was warmer than 1972 and there were significant dry spells.

For the February sowing (figure 7), the model yield rises rather faster than the observed increase in May. Later in June and July the growth rate of the model crop is much reduced by dry soil, but the actual crop continued to grow at a fast rate. Both the neutron probe measurements under some winter wheat, and the calculated deficits show deficits above 100 mm by the third week in June. The high growth rates are a bit at variance with this and it is possible that the early sowing caused a more extensive root system so that the crop had access to more water than is given in the model.

The discrepancy in May may be explained by the value of S used in the model. The value of S reflects the posture of the leaves and hence how the light penetrates the canopy. Early in the growing season the leaves are more vertical and S could very well be 0.8. Later in the season, as the leaves age the end portions tend to bend over and S = 0.7 may be more appropriate then. The model yield with S = 0.8 is also shown in figure 7, and the slightly better fit in May is apparent.

The late sowing in 1975 (figure 8) is the worst modelled crop of the three. The growth rate is much the same for the model and actual crops, but the model underestimates the actual yield at all times. The 2 week time step may be too long, or the water balance might be wrong. According to the model, all the available water was used up by the end of July, which seems a bit extreme.

The early sown crop in 1975 gave a grain yield of 6.3 t/ha DM (model 4.5 t/ha) and the late sown was 3.0 t/ha DM (model 1.9 t/ha). In both cases the model suffered from the large respiration loss problem at the end of the growing season, and better estimates of yield would be obtained by using the penultimate yield figure. In addition the harvest index was 50.6% for the early sown and 42.1% for the late sown, so there was some divergence from the 46% used in the model.

2. Winter Wheat. During 1979 some measurements of leaf area index and above ground crop weight were made available by courtesy of Bridget's EHF, (Mr P B Harris, Personal Communication). There were 10 winter wheat fields on the farm, and the experimental program consisted of taking 4 samples per field, each of 0.35 sq m. Each sample was assessed for total above ground dry matter and the leaf area index of 4 plants per field was determined. In addition the number of plants and tillers per sq m was assessed for each field as well as growth stage. These measurements were made in early May, mid-June and at the end of July. The grain yield for each field was measured at harvest.

The leaf area index and above ground dry weight were plotted against time and smooth curves were drawn by eye through the points. This was fairly straightforward for the dry weight curve, but was more subjective for the leaf area curve because the position of the peak of leaf area index was not known exactly, nor was the rate of rise or fall of leaf area. The curves were drawn keeping in mind that the typical shape of the leaf area curve with time is exponential at first and then linear. The mid-June measurement was assumed to be about a week before the leaf area peak.

In order to compare observed dry weight with the model some estimate of the variation of root dry weight during the season is required. This was found from Gregory et al, (1978). Figure 9 shows the fraction of total dry matter in the root for winter wheat from their results. The fraction is quite high in April, but falls to a 'constant' level by the end of May (about 9%). By using the graph in figure 9 the yields produced by the model were corrected to give above ground dry matter yields which can be compared directly with the Bridget's data.

The results for Oklahoma field are given in figure 10. This is fairly typical of the results for the 10 fields, and it shows that the model overestimates yields from May to early July, but that by the end of July the two are closer. In fact in about half the fields the model overestimated yields at the end of the growing season, and underestimated them in the other half.

The reason for large errors (observed cf model) for much of the early part of the growing season are not clear. The model may be inadequate of course, but during May and June rain fell frequently and the soil moisture deficit did not rise above 50 mm until early July. Thus it is unlikely that the crop was suffering water stress at this time. Errors in the measurement of leaf area and crop dry weight are possible, and the problem of getting representative samples for 10 fields is recognised. Tiller death was mentioned (P Harris, Personal Communication), and supposing this happened in mid-May then it is possible that the mid-June sample did not include these, so that the total yield was not in fact measured.

The results averaged over all the fields are more promising. Table 4 gives the above ground DM yields for each field (t/ha).

TABLE 4

FIELD	MODEL YIELD	OBSERVED YIELD	DIFFERENCE
Idaho	12.7	12.5	0.2
Moss	12.7	11.5	1.2
Vermont	10.1	14.6	-4.5
Iowa	9.8	11.7	-1.9
Ohio S.	13.8	11.2	2.6
Cow Paddock	13.8	12.5	1.3
Colorado	10.5	12.2	-1.7
Arkansas	12.7	14.8	-2.1
Nevada	13.4	10.7	2.7
Oklahoma	13.0	13.4	-0.4
Means	12.3	12.5	

The grain yields were 4.8 t/ha DM (observed) and 5.6 t/ha (model). In view of the fact that the effects of weeds, fungi, compaction etc are not included, this is a promising result. The model ought to give higher yields since it is really the yield which would be obtained with perfect husbandry ie. no disease, no pests, no combine losses etc.

Further work is needed on trials data to see if the model is of use in yield prediction work.

Any suggestions or comments should be made to the author.

M N Hough
Meteorological Office
Harrogate

June 1980

REFERENCES

Austin, R.B. and Jones, H.G. (1975). The physiology of wheat. PBI Annual Report for 1974, 20-73.

Biscoe, P.V., Gallagher, J.N., Littleton, E.J., Monteith, J.L. and Scott, R.K. (1975). Barley and its environment. IV. Sources of assimilate for the grain. J. Appl. Ecol., 12, 295-318.

Biscoe, P.V., Scott, R.K. and Monteith, J.L. (1975). Barley and its environment. III. Carbon budget of the stand. J. Appl. Ecol., 12, 269-93.

Biscoe, P.V. and Gallagher, J.N. (1977). Weather, dry matter production and yield. Environmental Effects on Crop Physiology. Landsberg, J.J. Cutting, C.V. eds. Academic Press.

Gallagher, J.N. and Biscoe, P.V. (1978). A physiological analysis of cereal yield. II. Partitioning of dry matter. Agricultural Progress. 53, 51-70.

Gregory, P.J., McGowan, M., Biscoe, P.V. and Hunter, B. (1978). Water relations of winter wheat. I. Growth of the root system. Journal of Agricultural Science, Cambridge 91, 91-102.

Ministry of Agriculture, Fisheries and Food (MAFF), (1967). Potential Transpiration. Technical Bulletin No. 16. HMSO London.

McCree, K. (1970). An equation for the rate of respiration of white clover plants grown under controlled conditions. Prediction and Measurement of Photosynthetic Productivity. I. Setlick ed. Centre for Agricultural Publishing and Documentation, Wageningen.

Monteith, J.L. (1963). Gas exchange in plant communities. Experimental Control of Plant Growth, 95-112. Academic Press.

Monteith, J.L. (1965). Light distribution and photosynthesis in field crops. Ann. Bot. London (NS), 29, 17-37

Monteith, J.L. (1977). Resistance of a partially wet canopy: whose equation fails? Boundary - layer Meteorology, 12, 379-83.

Russell, G. (1980). Crop evaporation, surface resistance and soil water status. Agricultural Meteorology, 21, 213-226.

Slatyer, R.O. (1973). Effects of short periods of water stress on leaf photosynthesis. Plant Response to Climatic Factors. Proceedings of Uppsala symposuim. Slatyer, R.O. ed. Unesco Paris.

Wellbank, P.J. (1975). Research on root growth at Rothamsted. MAFF Technical Bulletin No. 29. Soil Physical Conditions and Crop Production. HMSO London.

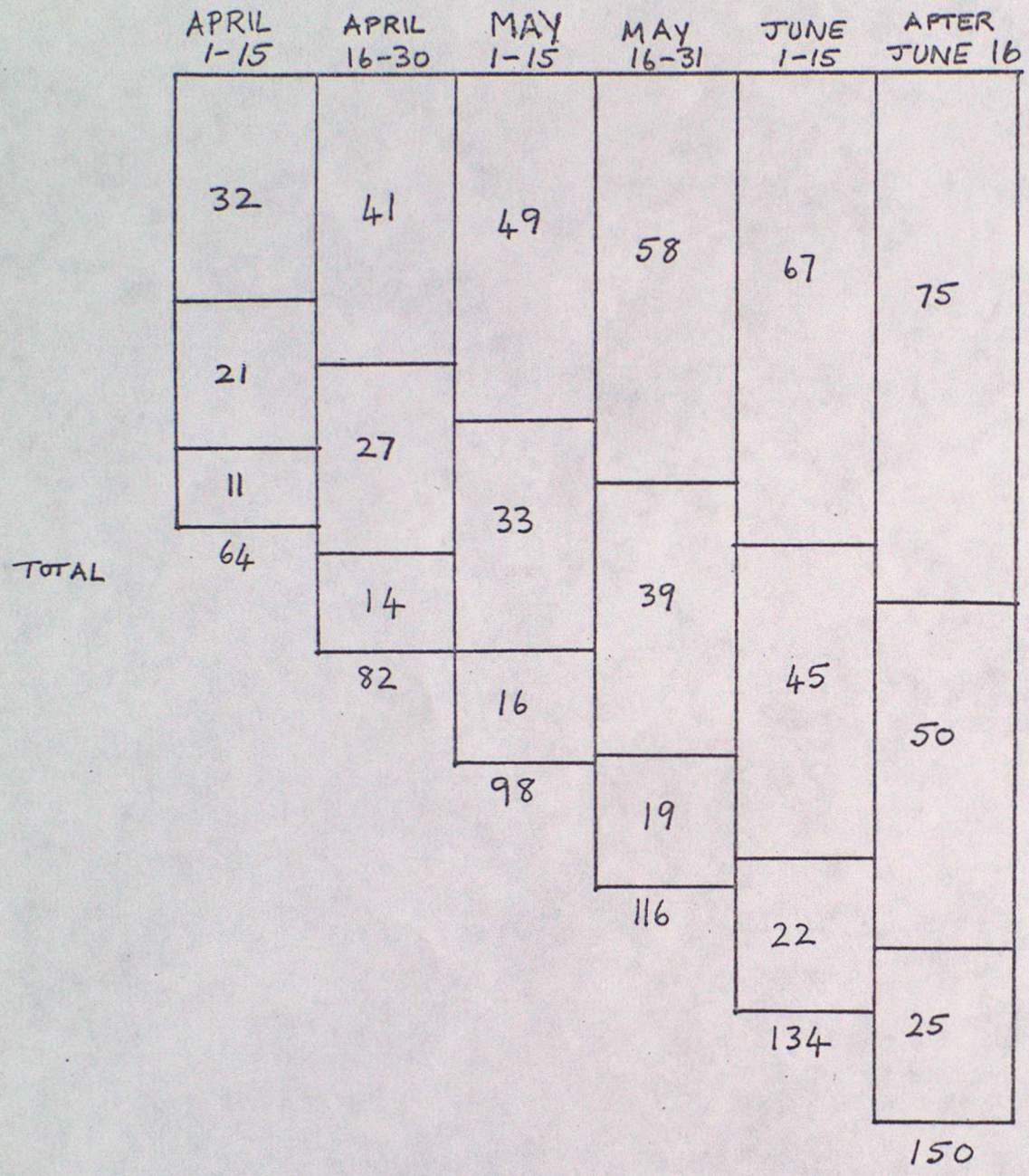

FIGURE 1.

AVAILABLE WATER (mm)

FOR WINTER WHEAT.

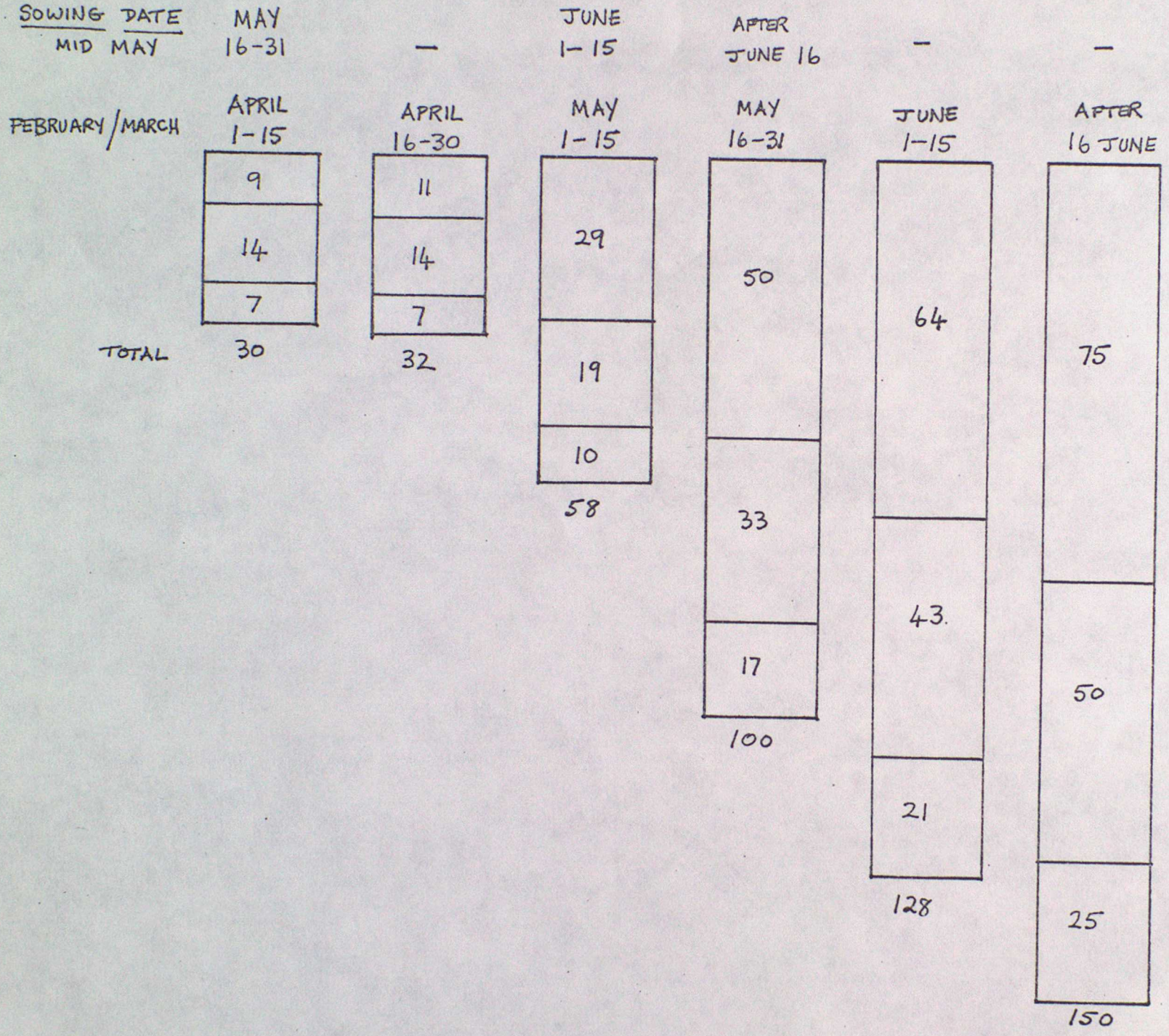

FIGURE 2.

AVAILABLE WATER (mm)

FOR SPRING BARLEY.

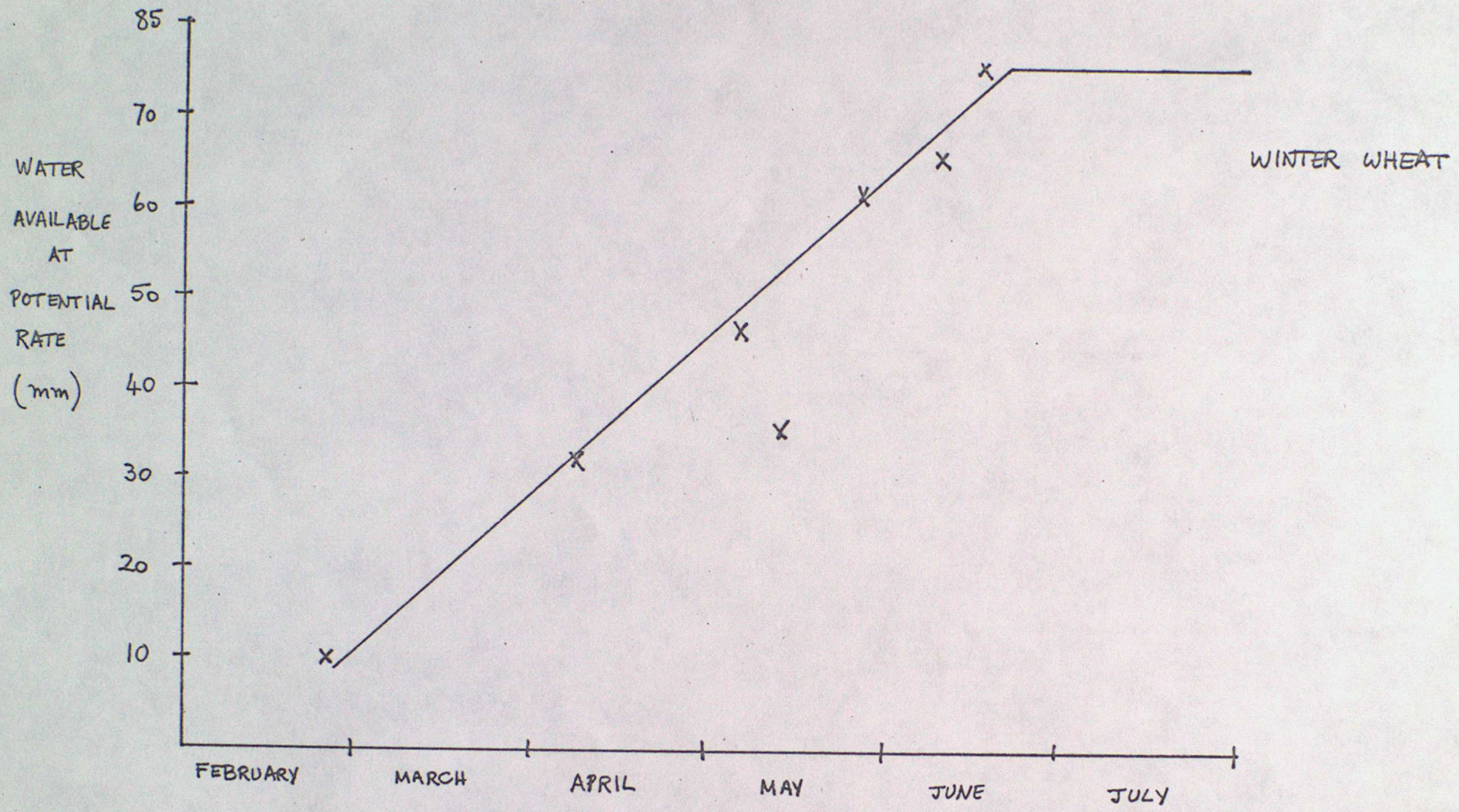

FIGURE 3. WATER AVAILABLE AT THE POTENTIAL RATE (1975 WINTER WHEAT CROP, SUTTON BONINGTON). THE LINE IS DRAWN BY EYE, NEGLECTING THE LOW POINT IN MID MAY.

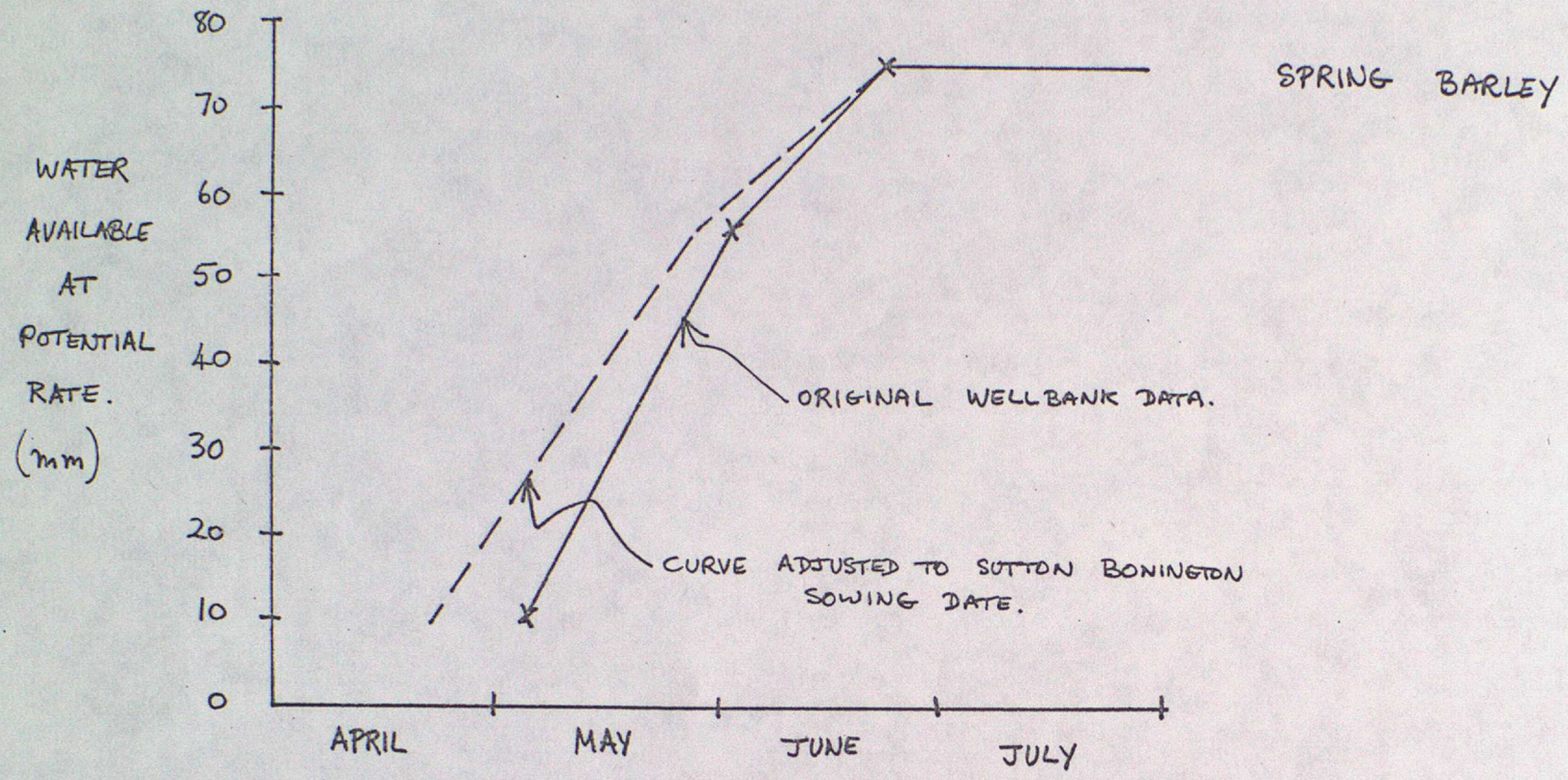

FIGURE 4. WATER AVAILABLE AT THE POTENTIAL RATE FOR SPRING BARLEY.

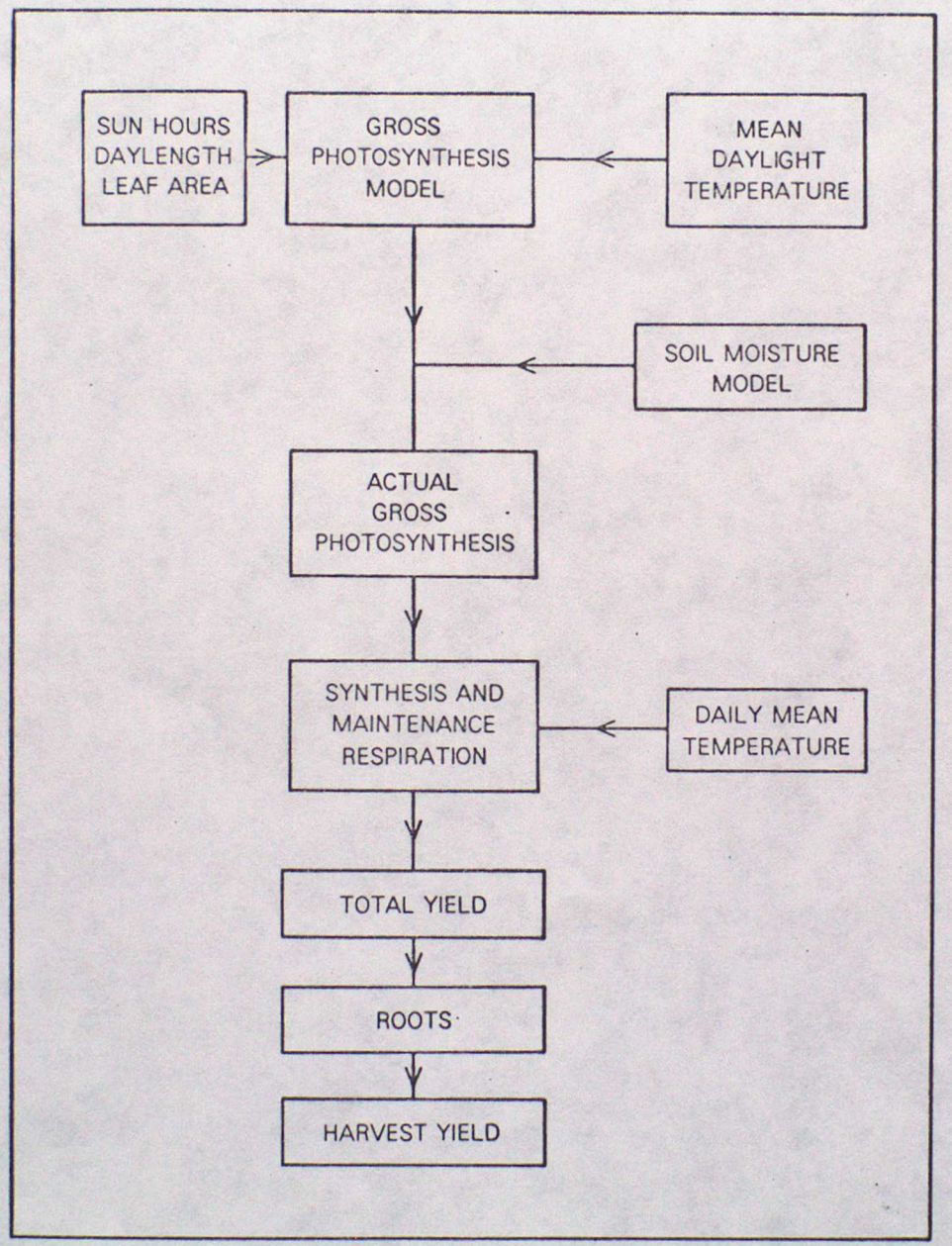

FIGURE 5. STEPS IN THE CALCULATION OF DRY MATTER PRODUCTION.

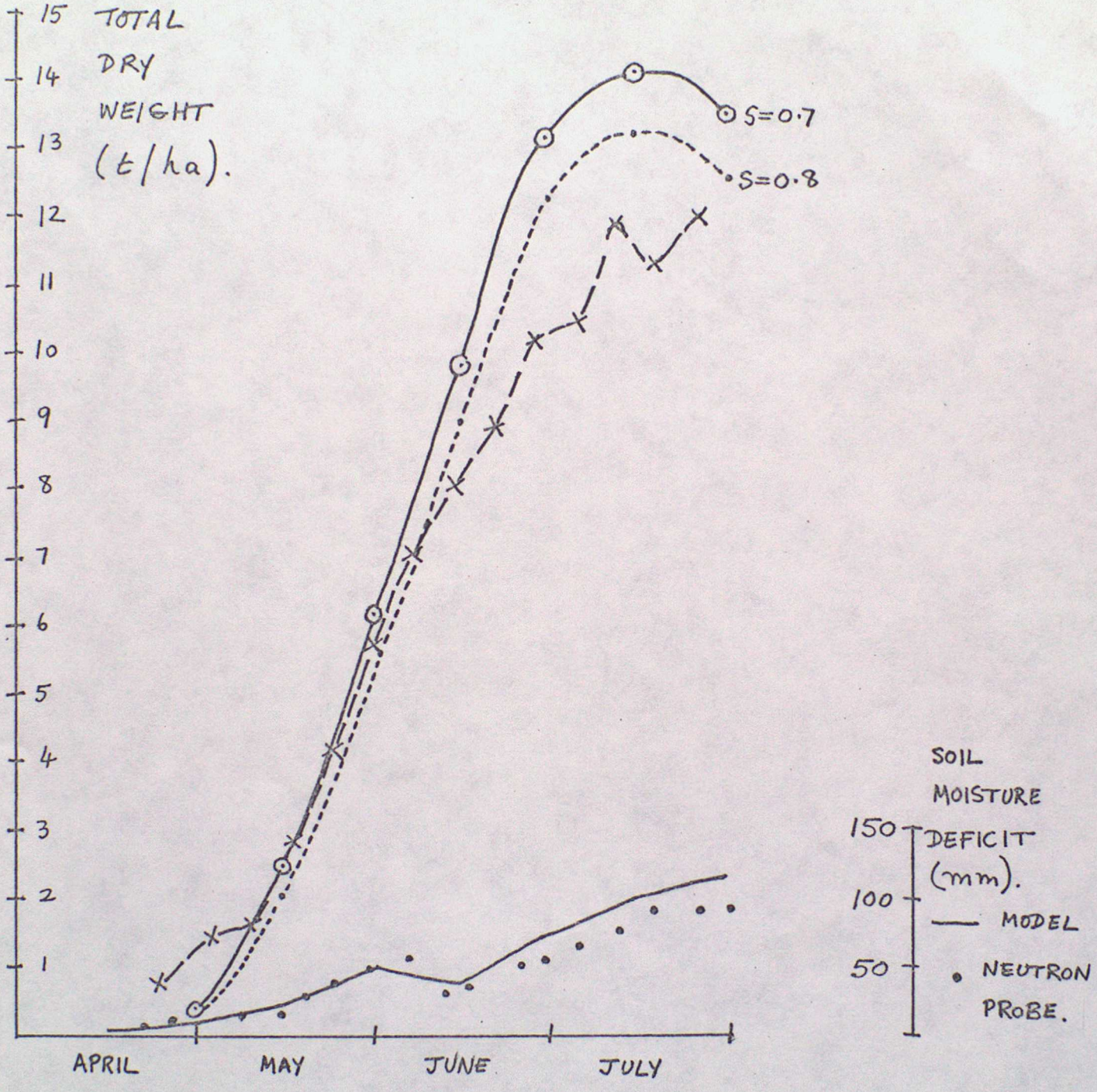

FIGURE 6. PROCTOR SPRING BARLEY 1972 @ SUTTON BONINGTON.

—x—x— OBSERVED DRY WEIGHT. (TOPS & ROOTS). SOWN MARCH 18th.

⊙—⊙ } MODEL WITH S = 0·7 or 0·8.
•- - -• }

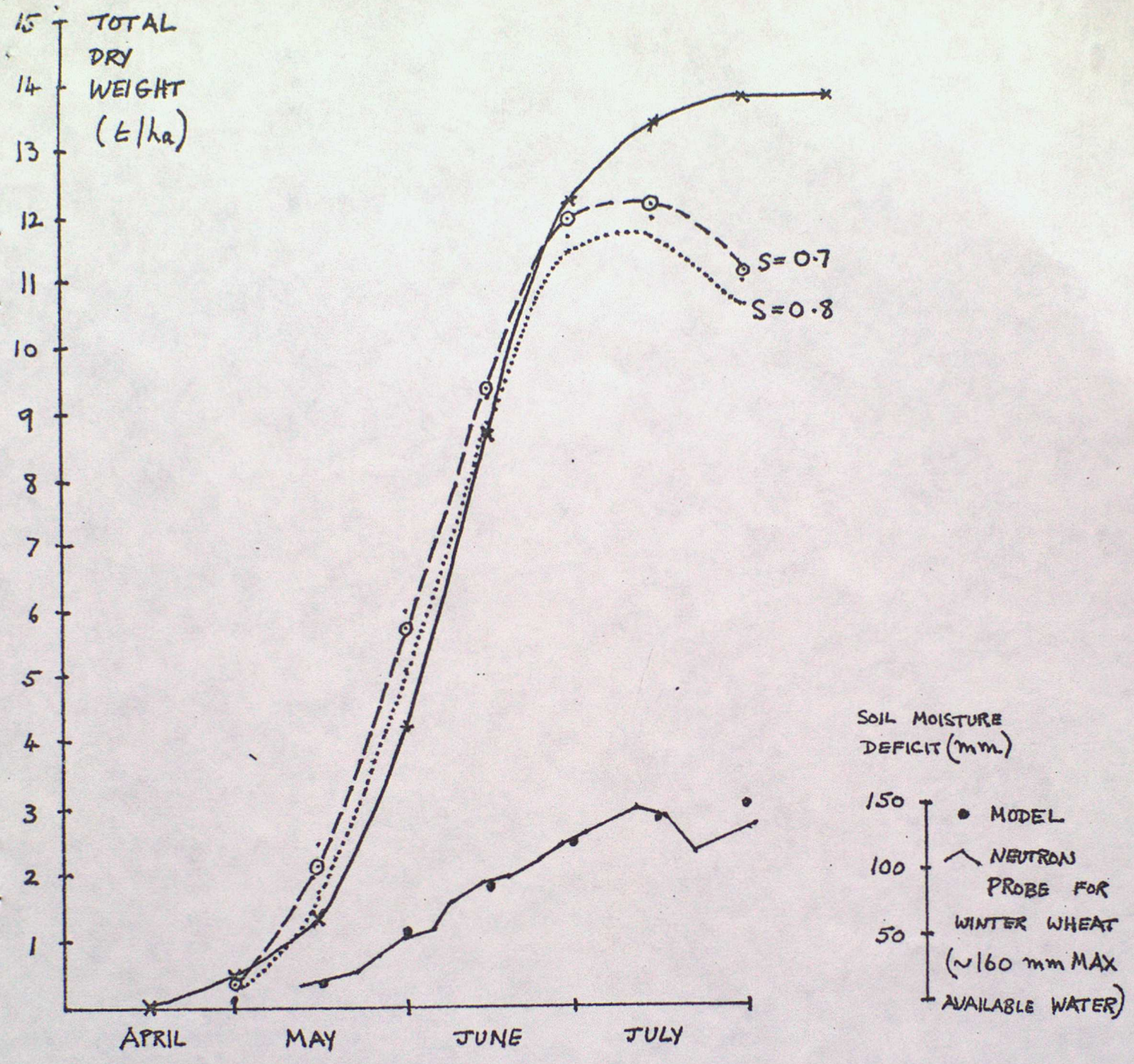

FIGURE 7. PROCTOR SPRING BARLEY 1975 @ SUTTON BONINGTON.

×—× OBSERVED DRY WEIGHT (TOPS & ROOTS). SOWN FEBRUARY 20th.

⊙- -⊙ } MODEL WITH S = 0·7 or 0·8.
•·····•

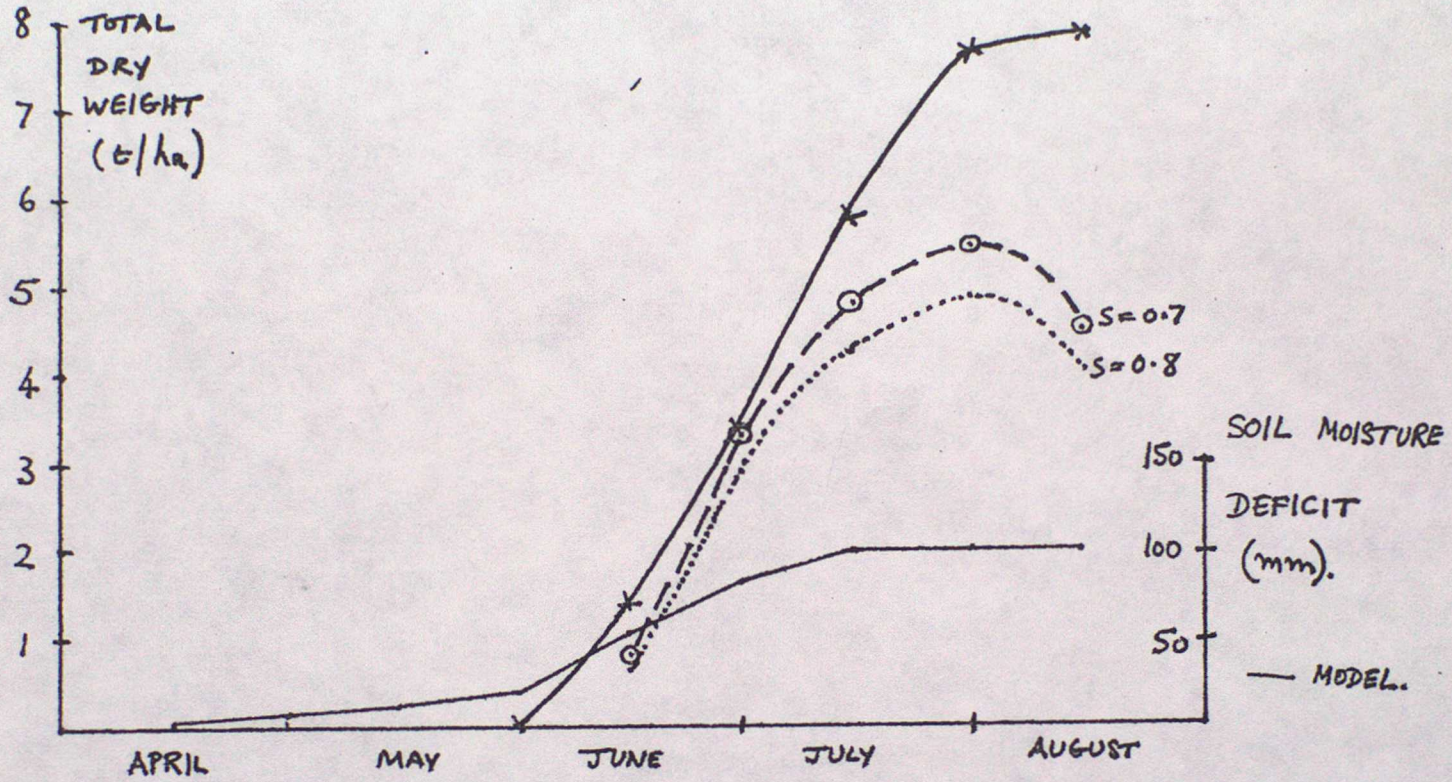

FIGURE 8. PROCTOR SPRING BARLEY 1975 @ SUTTON BONINGTON.

⟶ OBSERVED DRY WEIGHT (TOPS & ROOTS). SOWN MAY 14th.

⊙ - - ⊙ } MODEL WITH S=0·7 or 0·8.
..... }

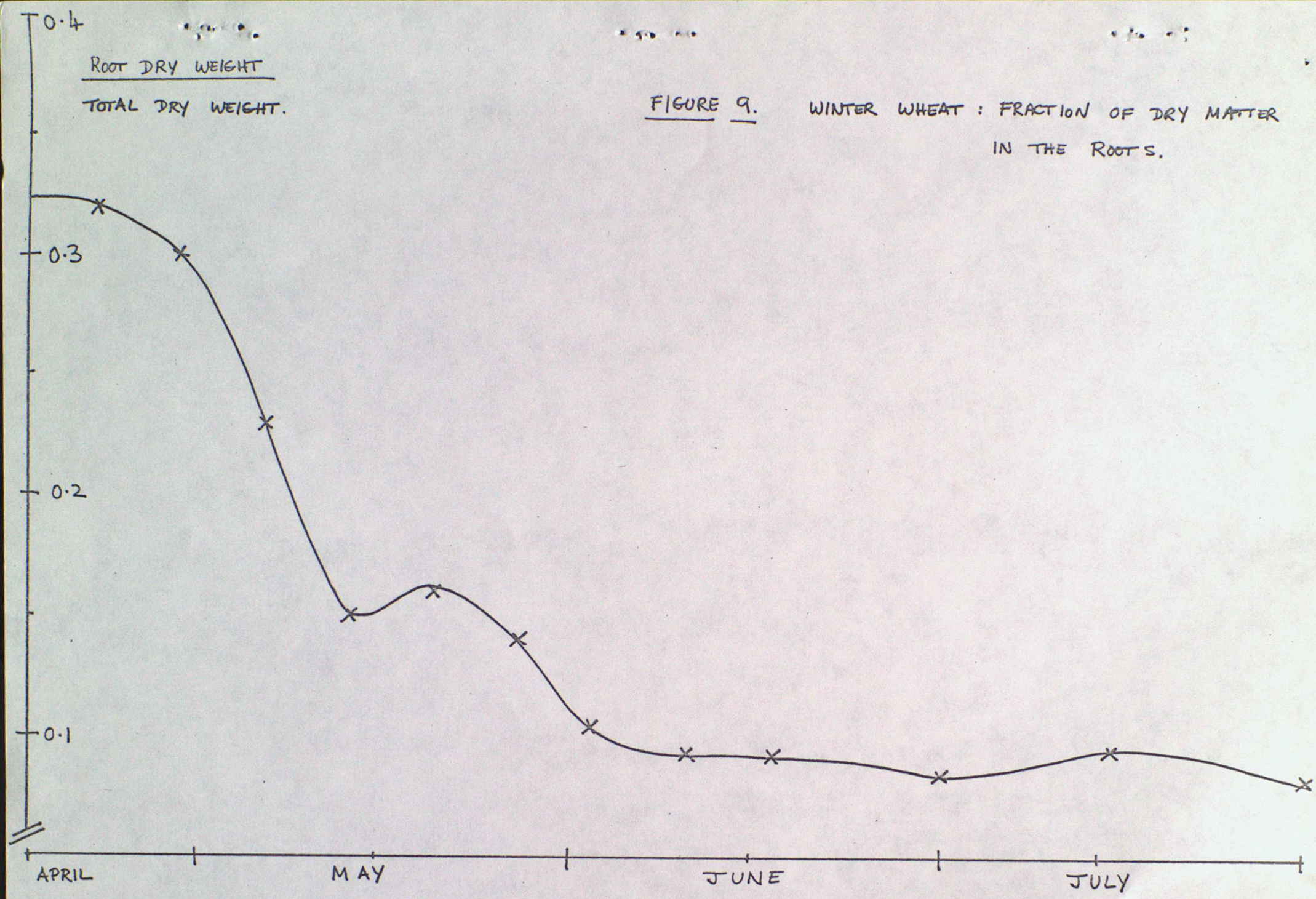

FIGURE 9. WINTER WHEAT : FRACTION OF DRY MATTER IN THE ROOTS.

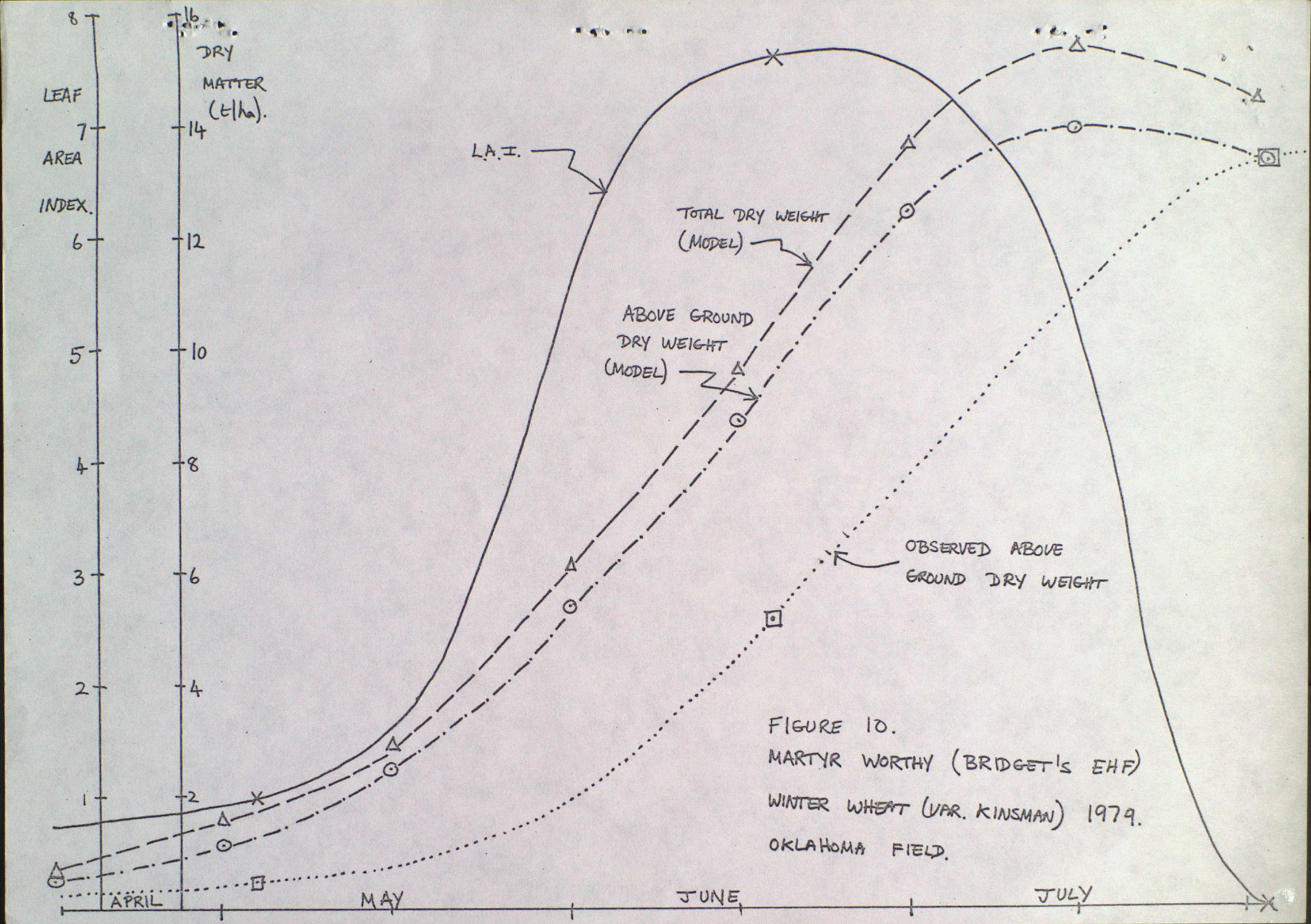

FIGURE 10.
MARTYR WORTHY (BRIDGET's EHF)
WINTER WHEAT (VAR. KINSMAN) 1979.
OKLAHOMA FIELD.